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A Hybrid Multi-Criteria Decision-Making Model Combining DANP with VIKOR for Sustainable Supplier Selection in Electronics Industry

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Abstract: Sustainability in operations and supply chains is becoming more popular among academics and practitioners through Sustainable Supplier Selection (SSS). In addition to balancing economic, social, and environmental factors, the awareness of the United Nations Sustainable Development Goals 2030 has affected the selection of long-term suppliers, ensuring green operations and sustainable supply chains. The criteria for SSS have multiple dimensions and are interdependent; this mimics the real-world scenario rather than assuming independently from an analytic hierarchy process. We use the multi-criteria decision-making (MCDM) model, combining DEMATEL-based on ANP (called DANP) with VIKOR, to solve the SSS problem. The DANP method is used to model and assess the interdependent relationships between criteria. Then, ranking the available alternatives and selecting the best one can be accomplished using the VIKOR method. We consider the electronic manufacturing industry in Taiwan as an empirical case. This study, in addition to selecting the best sustainable supplier, demonstrates the use of influential network relationship maps to analyze and improve the gaps in each dimension and criterion.

Keywords: sustainable supplier selection; multi-criteria decision-making; DANP; VIKOR; electronics industry

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1. Introduction

A manufacturing or service organization's supplier selection is a critical issue today as it impacts the products and services provided by the organization. A supplier selection process is crucial to the success of a supply chain, in terms of the quality of products and services delivered, and organizational effectiveness [1]. Supplier selection refers to the process of finding, analyzing, and contracting with suppliers [2]. Among the main goals of the supplier selection process are risk mitigation, maximization of total value for the buyer, and establishing warm and long-term relationships between suppliers and buyers [3]. Organizations rely heavily on the selection process to succeed, which consumes a considerable amount of resources. A successful business is able to lower its purchasing costs and increase competitiveness by choosing the right suppliers [4].

A growing concern for economic and environmental sustainability has become a major concern for industries around the world since the United Nations declared the Sustainable Development Goals 2030 [5]. Sustainability includes three dimensions: economic, environmental, and social. These dimensions informally are referred to as profits, planets, and people [6]. Sustainability can be amalgamated with supplier selection, a term called Sustainable Supplier Selection (SSS).

Supplier selection has traditionally been driven by the economic interests of the organization [7]. When selecting suppliers solely on the basis of profit, some crucial considerations may be overlooked, including environmental and social concerns [8]. Therefore, organizations can gain a significant competitive advantage over competitors by considering environmental, social, and economic factors in supplier selection. Furthermore, as a result of the climate change of our planet and its impacts, SSS has become more imperative than ever before.

Looking back on the past year, the environment has been full of many changes and challenges. Given a resurging pandemic, economic and trade fluctuations, port congestion, and materials shortage, a range of uncertainties have tested the adaptability and operational resilience of businesses [9]. Extreme weather effects due to climate change are also ubiquitous [10]. For the survival of humanity, all countries have accelerated their efforts to take more aggressive action while thinking about ways to live in harmony with nature. Many industries continue to focus on improving the efficiency of materials, water, and energy as well as the application of emerging carbon technologies and the development of new business opportunities and encouraging the participation of suppliers to build a resilient value chain from the inside out [11]. Among many types of industry, one which has the highest impact on sustainability is the electronics industry [12]. Air quality and temperature are affected by greenhouse gasses emitted by the electronic manufacturing industry [13]. The materials used in the manufacturing process of electronics industry, such as plastic, steel, and glass, have a great contribution to the environment. When electronic waste is improperly handled, hazardous materials that contain harmful chemicals are released into the environment and damage it as a result [14]. Some developing countries face this serious problem, resulting in environmental pollution and threatening residents' health. Moreover, in developed countries, workers and nearby communities may face a considerable risk of injury or death when recycling discarded electronic equipment. In order to prevent irreversible pollution of the environment caused by the disposal of hazardous waste and the appropriate recycling of harmful substances, the electronic manufacturing industry needs to invest heavily in resources and management measures [15]. This is the main reason for our focus on SSS; environmentally friendly materials maintaining high quality, reasonable cost, timely fashion, and social responsibility are expected to be evaluated on the issue of sustainability.

As SSS is a kind of Multi-Criteria Decision-Making (MCDM) problem, we propose a hybrid MCDM model combining a Decision-making Trial and Evaluation Laboratory (DEMATEL) method with an Analytic Network Process (ANP) and VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method in this study. The DEMATEL method has been used in many fields to understand the interrelationship among the dimensions and consider the significance of different weight dimensions or criteria. For example, a hybrid rough-fuzzy DEMATEL-TOPSIS method was proposed in supplier selection process [16]. The integration of DEMATEL and COPRAS methods has been applied to prioritize green suppliers [17]. The ANP approach is designed to make decisions based on many different criteria by assessing its weight. A suitable MCDM model by combining ANP, entropy weight, and TOPSIS was applied in the building materials supplier selection [18]. A hybrid model combining DEMATEL and ANP, which is called DEMATEL-based ANP (DANP), has been successfully implemented in the solution of a wide range of MCDM problems. Dincer et al. [19] proposed a hybrid MCDM method combining DANP and MOORA for evaluation of financial services. The VIKOR methodology can be employed to rank the available alternatives and select the most suitable supplier among them. A new MCDM model based on an extended VIKOR was proposed to select the proper healthcare device suppliers [20]. The combination of DEMATEL and VIKOR approaches was introduced by Qi et al. [21] for analyzing sustainability in the energy industry.

In this paper, we present a hybrid MCDM model to provide the ranking of sustainable suppliers and select the best one. In addition to ranking and selecting suppliers, we also offer how to increase suppliers' performance by reducing gaps across each dimension or criterion using the VIKOR method. This can be accomplished by calculating the individual gaps and group utility values for each alternative. Moreover, this study will use the DEMATEL method to develop an influential network relationship map as not yet explored by Chang et al. [22]. The selection and evaluation of sustainable suppliers should consider ethics, health and safety, and labor conditions [23]. We will investigate the interrelationships of a set of criteria categorized according to the economic, environmental, and social dimensions in the triple bottom line framework [24]. Therefore, a hybrid MCDM model for sustainable supplier selection and improvement is illustrated using an empirical case study of the display manufacturing industry in Taiwan.

The rest of the paper is organized as follows: the second section presents the relevant literature about SSS dimensions and criteria; in Section 3, we develop a hybrid MCDM model combining DANP with VIKOR; Section 4 presents the empirical case study and highlights the managerial implications. In the Section 5, we draw a conclusion.

2. Sustainable Supplier Selection Dimensions and Criteria

To begin this study, a review of the literature identified three dimensions and fifteen critical evaluation criteria for SSS in the global display manufacturing industry. The first five criteria related to the economic dimension; the next five were associated with the environmental; and the remainder corresponded with the social dimension. In searching the prior literature, key terms were used to identify the criteria, such as "criterion for sustainable supplier selection", "supplier selection process in the electronics industry", and "sustainability incorporation in supplier selection". The Google Scholar, Scopus, and Web of Science databases were used to explore the literature. We only select the latest literature; the search period ranges from 2018 to 2022. We have found and examined more than 50 papers. However, in the end, we only chose 17 journal papers that aligned with our study. Furthermore, we have analyzed the selected criteria based on the case study in the electronics industry with consideration of sustainability factors as our research focus. Green production policy, practice of sustainable future, and eco-friendly materials used are some criteria that emphasize the sustainability concern. The criterion of using smart manufacturing systems has also been raised as we are currently in the fourth industrial revolution. In addition, some aspects related to ethics, health and safety, and labor conditions were incorporated into the selection process [23]. The dimensions and evaluation criteria, together with the definitions identified for SSS in the global display manufacturing industry, are listed in Table 1.

Table 1. The influence dimensions and criteria of comprehensive sustainable supplier selection in the electronics industry.

Dimension	Criteria	Definition	Reference
Economic (D_1)	Quality of component (C_1)	Performance of components to meet the production requirements.	Orji and Ojadi [25]
	Delivery time (C_2)	Timeframe by which the supplier must deliver its components.	Jain and Singh [26]
	Price of component (C_3)	Value of components as expressed in money.	Fallahpour et al. [27]
	Technical capability (C_4)	Have proper technology to stabilize component quality and decrease waste in manufacturing.	Alavi et al. [28]
	Manufacturing capability (C_5)	Use smart manufacturing systems to produce components and improve operations.	Suraraksa and Shin [29]

Table 1. *Cont.*

Dimension	Criteria	Definition	Reference
Environmental (D_2)	Environmental and energy management system (C_6)	Implementation of ISO 14001 and 50001 standards in all business segments within the company.	Durmic [30]
	Green manufacturing policy (C_7)	Efforts made by the supplier to reduce pollution (carbon emissions) and improve green production.	Chen et al. [16]
	Practice of sustainable future (C_8)	The potential of suppliers to apply clean technologies and innovate newer clean technologies, processes, techniques, and methodologies.	Khan and Ali [31]
	Compliance of material used (C_9)	The amount of eco-friendly (non-harmful) materials used in production and packaging.	Rani et al. [32]
	Recycling product and process (C_{10})	Reduce waste by reusing materials and products.	Stevic et al. [33]
Social (D_3)	Supplier social responsibility (C_{11})	Community engagement and volunteer works.	Khan et al. [34]
	Employee welfare and growth (C_{12})	The process of making employees more knowledgeable and skilled in a particular area of employment.	Ecer and Pamucar [35]
	Organizational culture development (C_{13})	Create a conducive organizational culture for their employees to apply sustainability concepts.	Kusi-Sarpong et al. [36]
	Regulation compliance (C_{14})	The suppliers adhere to local laws and regulations, observe their legal obligations, and work towards improving morals in the public sphere.	Hoseini et al. [37]
	Occupational health and safety (C_{15})	Implementation of measures concerning the protection of health and life of employees.	Kannan et al. [38]

Selecting sustainable suppliers under the economic dimension (D_1) is of the utmost importance since these criteria examine how the supplier's activities affect the local economy [39]. Within the economic dimension, we have identified five criteria: quality of component; delivery time; price of component; technical capability and manufacturing capability. Prior published studies suggest that quality of component (C_1) can be measured by conforming to relevant standards, specifications, and requirements [25]. Jain and Singh [26] found that the on-time delivery (C_2) of the products by suppliers is crucial for industry. The price of a component (C_3) is typically determined by the amount of money that represents the value of the components [27]. Clean and green technology (C_4) utilized in production and recycling products can increase product quality and reduce production waste [28]. In mass customization, technology and production capability (C_5) are used to solve the problem of supplier selection [29].

The environmental dimension (D_2) of this study consists of five criteria, namely, environmental and energy management system; green manufacturing policy; practice of sustainable future; compliance of material used; and recycling product and process. Environmental performance improvements and competitiveness can be achieved by implementing a functional environmental and energy management system (C_6) and conducting regular audits [30]. The green production process (C_7) encourages suppliers to promote sustainable development by ensuring their products meet environmental protection guidelines [16]. There are many incentives provided to the supplier when they implement the latest environment-friendly technologies (C_8) to encourage them to adopt sustainable practices [31]. Rani et al. [32] determined the level of sustainable materials (C_9) utilized in the production processes as a benefit type of criteria. Stevic et al. [33] defined recycling criteria as the reuse of materials and products (C_{10}) in line with the effort of reducing waste.

Selecting sustainable suppliers is highly dependent on the social dimension (D_3) as it pertains to sustainable supply chains [40]. In this study, we have classified five criteria within the social dimension: supplier social responsibility; employee welfare and growth; organizational culture development; regulation compliance, and occupational health and safety. Supplier social responsibility (C_{11}) refers to the extent of their community engagement for stakeholder and shareholder benefit and the extent to which they contribute to sustainability [34]. In order to improve levels of employee welfare and development (C_{12}), the supplier has to conduct staff training to increase the knowledge and skills of employees [35]. Organizational culture development (C_{13}) entails embracing new methods and technologies for sustainable management while promoting a culture of innovation [36]. In order to achieve sustainability objectives, suppliers must comply with policies and regulations (C_{14}) adopted by the industrial sector and other regulatory agencies [37]. Implementing measures to protect employees at work and minimize accidents (C_{15}) can facilitate SSS [38].

We consider Corporation U as one of the largest Taiwanese companies that has been dedicated to the development of display manufacturing for electronic products since 1996. Corporation U offers display panel products; in particular, it specializes in optoelectronic solutions for smart retail, smart medical, smart transportation, smart education, and entertainment. As the world faces severe climate issues, Corporation U has made comprehensive arrangements in all respects, and set positive goals to drive themselves as they commit to zero carbon emissions in their global offices by 2030 and full use of renewable energy by 2050. At the same time, they also assist in the industry energy transformation with their energy business to contribute to world climate action. Corporation U provides sustainable products that are beneficial to raw materials recycling, re-use, and energy saving. Working together with the supplier, this corporation launched the world's first environmentally friendly laptop using recycled materials. In terms of waste reduction, Corporation U adopted a box-sharing approach in cooperation with suppliers to cut down on the generation of waste plastic packaging materials. We denote three dimensions and 15 criteria to form a hierarchy for SSS as shown in Figure 1. In this study, we compare suppliers' performance and apply methods to reduce the remaining gaps to achieve the aspiration levels by improving the performance of the relevant dimensions and criteria.

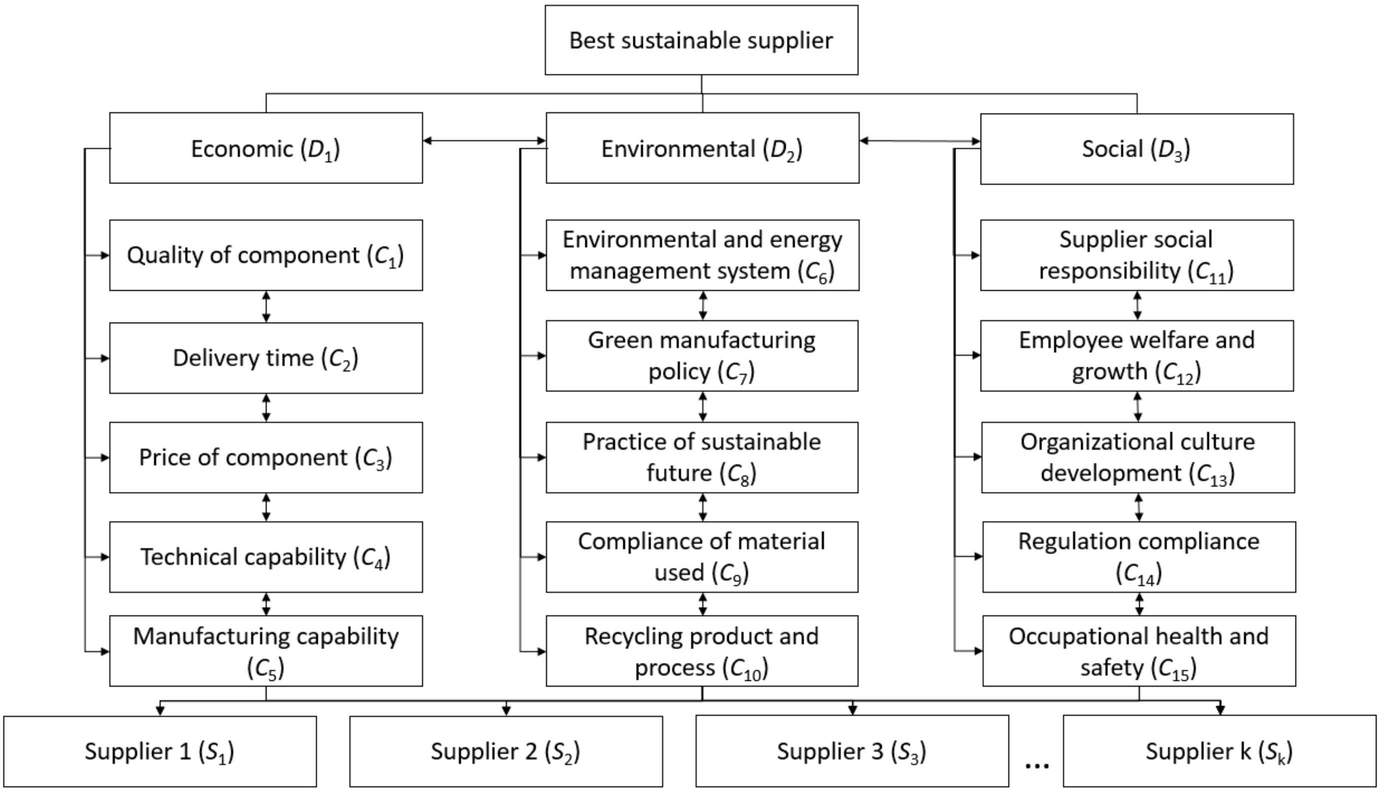


Figure 1. The hierarchy of sustainable supplier selection in electronics industry.

3. A Hybrid MCDM Model

A hybrid MCDM model includes both DEMATEL and ANP concepts to determine the DANP influence weights and the VIKOR method to assess the performance gaps in each criterion and dimension. Based on the DEMATEL technique, the SSS criteria were derived from their degree of influence with the scale ranging from 0 (no influence) to 4 (very high influence) and applied to the formation of the ANP supermatrix (unweighted and weighted supermatrices). In addition to handling inner dependencies within dimensions, the ANP also handles outer dependencies between dimensions. A hybrid MCDM model using the DANP method has been widely utilized in many fields to determine the influence weights, such as measurement of corporate sustainability indicators [41], green building rating systems [42], and financial service innovation strategies [43]. Ranking and improving the overall performance gap among the criteria and dimensions using the VIKOR method can be found in [44,45].

As depicted in Figure 2, a hybrid MCDM model includes three stages: (1) deriving the total influence matrix and building the Influential Network Relation Map (INRM) between criteria by the DEMATEL technique; (2) computing each criterion's influential weights by applying the ANP concept; and (3) ranking and improving the dimensions or criteria prioritization using the VIKOR method for reducing the remaining gaps to achieve the level of aspiration, which refers to the best performance score. The gap between criteria or dimensions is assessed by calculating the individual gaps and group utility values for each alternative. The individual gaps value represents the difference between the performance of an alternative and the best performance among all alternatives for a particular criterion. On the other hand, the group utility value represents the difference between the performance of an alternative and the ideal solution that minimizes the overall deviation from the best performance for all criteria.

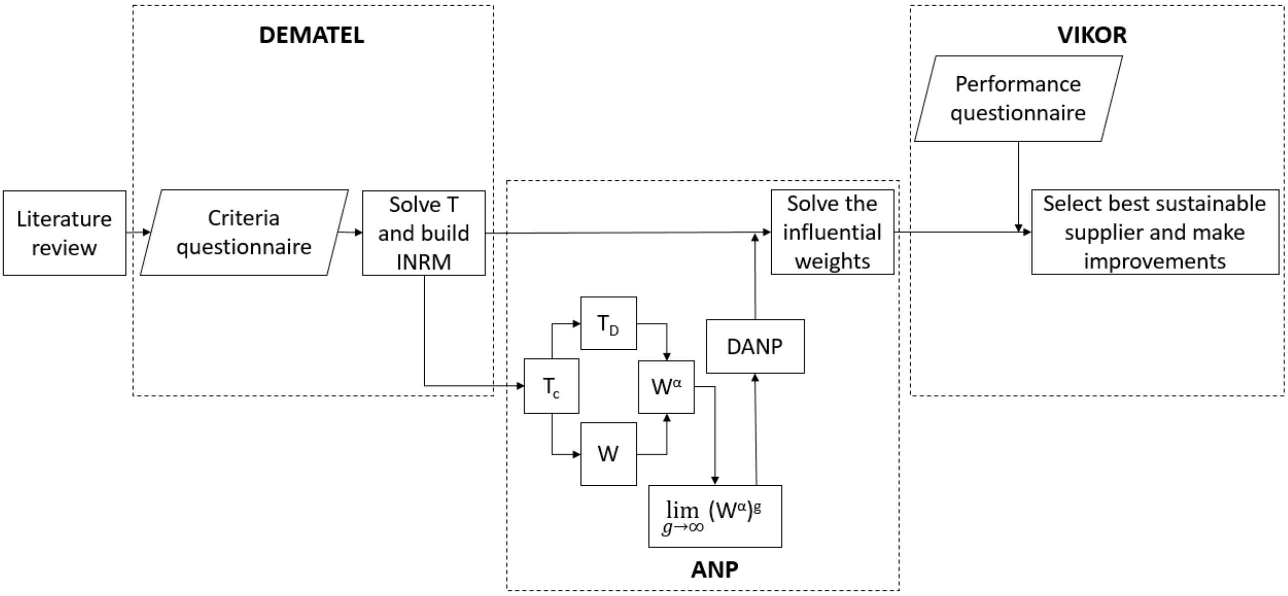


Figure 2. Proposed hybrid MCDM model combining DANP and VIKOR.

3.1. Stage I

There are three steps involved in DEMATEL and INRM:

Step 1: Calculate the scores of the direct-influence matrix $\boldsymbol{A}$. A mutual influence relationship between each criterion is assessed based on expert opinions in the Taiwanese electronics industry who are familiar with SSS. A criteria questionnaire is made with the scale range from 0 to 4, which represents 0: absolutely no influence, 1: low influence, 2: medium influence, 3: high influence, and 4: very high influence. Expertise opinions are required as the input of the direct-influence matrix by a pairwise comparison. A notation of a_{ij} means that criterion i has an influence on criterion j. Then, average matrix $\boldsymbol{A} = [a_{ij}]_{n\times n}$ of mutual influence relationships can be generated as Equation (1). The numbers in matrix $\boldsymbol{A}$ can be obtained by taking the average value from all of the expertise inputs:

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}. \tag{1}$$

Step 2: Calculate the normalized direct-influence matrix $\boldsymbol{X}$. The derivation of normalized direct-influence matrix $\boldsymbol{X}$ is shown as Equation (2).

$$\boldsymbol{X} = \mathrm{z} \times \boldsymbol{A}, \tag{2}$$

where $z = \min_{i,j}\left\{\frac{1}{\max_i \sum_{j=1}^{n} a_{ij}}, \frac{1}{\max_j \sum_{i=1}^{n} a_{ij}}\right\}, \forall i, j \in \{1, 2, \ldots, n\}$.

The diagonal value of this matrix is zero. The maximum adds values of each row or column is one.

Step 3: Obtain the total-influence matrix $\boldsymbol{T}$. There are two types of total-influence matrix, $\boldsymbol{T}_C$ and $\boldsymbol{T}_D$, which refer to criteria and dimensions, respectively. It is possible to determine the continuous decrease in indirect effects of problems through the use of powers of $\boldsymbol{X}$, e.g., $\boldsymbol{X}^2, \boldsymbol{X}^3, \ldots, \boldsymbol{X}^h$, where $\boldsymbol{X} = [x_{ij}]_{n\times n}$, $0 \leq x_{ij} \leq 1$, $0 \leq \sum_i x_{ij} \leq 1$, $0 \leq \sum_j x_{ij} \leq 1$, and at least one row or column of summation equals one, but not every row or column;

then, we can guarantee that $\lim_{h\to 0} \boldsymbol{X}^h = [0]_{n\times n}$. Thus, the total-influence matrix $\boldsymbol{T}$ is obtained by Equation (3).

$$\boldsymbol{T} = \boldsymbol{X} + \boldsymbol{X}^2 + \ldots + \boldsymbol{X}^h = \boldsymbol{X}(\boldsymbol{I} - \boldsymbol{X})^{-1}, \text{ when } \lim_{h\to 0} \boldsymbol{X}^h = [0]_{n\times n}, \tag{3}$$

where $\boldsymbol{I}$ indicates the unit matrix.

The sum of the rows and columns of the total-influence matrix $\boldsymbol{T}$ are in separate expression as vector $\boldsymbol{r}$ in Equation (4) and $\boldsymbol{s}$ in Equation (5), respectively.

$$\boldsymbol{r} = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_D^{ij}\right]_{nx1}, \ \forall\, i,\ j\ \in\ \{1,\ 2,\ \ldots,\ n\}, \tag{4}$$

and

$$\boldsymbol{s} = [s_j]_{nx1} = \left[\sum_{i=1}^{n} t_D^{ij}\right]'_{1xn}, \ \forall\, i,\ j\ \in\ \{1,\ 2,\ \ldots,\ n\}, \tag{5}$$

where the prime ($'$) indicates the transpose. Additionally, r_i represents the sum of influences given on criteria i and s_j represents the sum of influences received from criteria j. Moreover, the summation ($r_i + s_i$) represents the level of criteria i which has role in the problem, and the difference ($r_i - s_i$) represents the net contribution of criteria i to the problem. In cases where the difference is positive, it means criteria i affects other criteria. Otherwise, criteria i is affected by other criteria. These results are then utilized to build the INRM, which can give insights for improvement.

3.2. Stage II

There are five steps to describe DANP influential weights:

Step 1: Calculate the normalized matrix $\boldsymbol{T}_c^{\alpha}$ by dimensions. First, we have to normalize the total-influence matrix $\boldsymbol{T}_C$ by dimensions. This means normalizing each element of the criteria within its dimension. Then, we can obtain a new normalized matrix $\boldsymbol{T}_c^{\alpha}$ as shown in Equation (6).

$$\boldsymbol{T}_c^{\alpha} = \begin{array}{c} \\ \boldsymbol{D}_1 \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ \vdots \\ \boldsymbol{D}_i \begin{array}{c} c_{i1} \\ c_{i2} \\ \vdots \\ c_{im_i} \end{array} \\ \vdots \\ \boldsymbol{D}_n \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} \overset{\begin{array}{ccccc} \boldsymbol{D}_1 & & \boldsymbol{D}_j & & \boldsymbol{D}_n \\ c_{11}\ldots c_{1m_1} & & c_{j1}\ldots c_{jm_j} & \cdots & c_{n1}\ldots c_{nm_n} \end{array}}{\begin{bmatrix} \boldsymbol{T}_c^{\alpha 11} & \cdots & \boldsymbol{T}_c^{\alpha 1j} & \cdots & \boldsymbol{T}_c^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{\alpha i1} & \cdots & \boldsymbol{T}_c^{\alpha ij} & \cdots & \boldsymbol{T}_c^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{T}_c^{\alpha n1} & \cdots & \boldsymbol{T}_c^{\alpha nj} & \cdots & \boldsymbol{T}_c^{\alpha nn} \end{bmatrix}} \tag{6}$$

The explanation for normalization $\boldsymbol{T}_c^{\alpha 11}$ is as follows.

$$\boldsymbol{T}_c{}^{\alpha 11} = \begin{bmatrix} t_{c11}^{11}/d_{c1}^{11} & \cdots & t_{c1j}^{11}/d_{c1}^{11} & \cdots & t_{c1m_1}^{11}/d_{c1}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{11}/d_{ci}^{11} & \cdots & t_{cij}^{11}/d_{ci}^{11} & \cdots & t_{cim_1}^{11}/d_{ci}^{11} \\ \vdots & & \vdots & & \vdots \\ t_{cm_1 1}^{11}/d_{cm_1}^{11} & \cdots & t_{cm_1 j}^{11}/d_{cm_1}^{11} & \cdots & t_{cm_1 m_1}^{11}/d_{cm_1}^{11} \end{bmatrix} = \begin{bmatrix} t_{c11}^{\alpha 11} & \cdots & t_{c1j}^{\alpha 11} & \cdots & t_{c1m_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{\alpha 11} & \cdots & t_{cij}^{\alpha 11} & \cdots & t_{cim_1}^{\alpha 11} \\ \vdots & & \vdots & & \vdots \\ t_{cm_1 1}^{\alpha 11} & \cdots & t_{cm_1 j}^{\alpha 11} & \cdots & t_{cm_1 m_1}^{\alpha 11} \end{bmatrix},$$

where $d_{ci}^{11} = \sum_{j=1}^{m_1} t_{cij}^{11}$, i = 1, 2, . . . , m_1.

Step 2: Calculate the unweighted supermatrix $\boldsymbol{W}$. Conduct the transpose operator of the normalized matrix $\boldsymbol{T}_c^{\alpha}$, that is $\boldsymbol{W} = (\boldsymbol{T}_c^{\alpha})'$, and is given by

$$\boldsymbol{W} = (\boldsymbol{T}_c^{\alpha})' = \begin{array}{c} \\ D_1 \begin{array}{c} c_{11} \\ c_{12} \\ \vdots \\ c_{1m_1} \end{array} \\ \vdots \\ D_j \begin{array}{c} c_{j1} \\ c_{j2} \\ \vdots \\ c_{jm_j} \end{array} \\ \vdots \\ D_n \begin{array}{c} c_{n1} \\ c_{n2} \\ \vdots \\ c_{nm_n} \end{array} \end{array} \overset{\begin{array}{ccccc} D_1 & & D_i & & D_n \\ c_{11}\ldots c_{1m_1} & & c_{i1}\ldots c_{im_i} & \cdots & c_{n1}\ldots c_{nm_n} \end{array}}{\begin{bmatrix} \boldsymbol{W}^{11} & \cdots & \boldsymbol{W}^{i1} & \cdots & \boldsymbol{W}^{n1} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{W}^{1j} & \cdots & \boldsymbol{W}^{ij} & \cdots & \boldsymbol{W}^{nj} \\ \vdots & & \vdots & & \vdots \\ \boldsymbol{W}^{1n} & \cdots & \boldsymbol{W}^{in} & \cdots & \boldsymbol{W}^{nn} \end{bmatrix}}$$

As a result, $\boldsymbol{W}^{11}$, $\boldsymbol{W}^{n1}$, $\boldsymbol{W}^{1n}$, and $\boldsymbol{W}^{nn}$ in the above formula are the same value as $\boldsymbol{T}_c^{\alpha 11}$, $\boldsymbol{T}_c^{\alpha n1}$, $\boldsymbol{T}_c^{\alpha 1n}$, and $\boldsymbol{T}_c^{\alpha nn}$ in Equation (6), respectively.

Step 3: Calculate the normalized supermatrix $\boldsymbol{T}_D^{\alpha}$ by dimensions. The total-influence matrix $\boldsymbol{T}_D$ is shown as follows.

$$\boldsymbol{T}_D = \begin{bmatrix} t_D^{11} & \cdots & t_D^{1j} & \cdots & t_D^{1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{i1} & \cdots & t_D^{ij} & \cdots & t_D^{in} \\ \vdots & & \vdots & & \vdots \\ t_D^{n1} & \cdots & t_D^{nj} & \cdots & t_D^{nn} \end{bmatrix}$$

where t_D^{ij} is the element of normalized dimension in row i and column j.

For normalization purposes, conduct summations for each column of the total-influence matrix $\boldsymbol{T}_D$. Thus, we can derive a new normalized matrix $\boldsymbol{T}_D^{\alpha}$, as shown in Equation (7).

$$\boldsymbol{T}_D^{\alpha} = \begin{bmatrix} t_D^{11}/d_1 & \cdots & t_D^{1j}/d_1 & \cdots & t_D^{1n}/d_1 \\ \vdots & & \vdots & & \vdots \\ t_D^{i1}/d_i & \cdots & t_D^{ij}/d_i & \cdots & t_D^{in}/d_i \\ \vdots & & \vdots & & \vdots \\ t_D^{n1}/d_n & \cdots & t_D^{nj}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} = \begin{bmatrix} t_D^{\alpha 11} & \cdots & t_D^{\alpha 1j} & \cdots & t_D^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha i1} & \cdots & t_D^{\alpha ij} & \cdots & t_D^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha n1} & \cdots & t_D^{\alpha nj} & \cdots & t_D^{\alpha nn} \end{bmatrix} \quad (7)$$

where $t_D^{\alpha ij} = t_D^{ij}/d_i$ and $d_i = \sum_{j=1}^{n} t_D^{ij}$.

Step 4: Obtain the weighted supermatrix $\boldsymbol{W}^{\alpha}$, as derived by Equation (8).

$$\boldsymbol{W}^{\alpha} = \boldsymbol{T}_D^{\alpha}\,\boldsymbol{W} = \begin{bmatrix} t_D^{\alpha 11} \times \boldsymbol{W}^{11} & \cdots & t_D^{\alpha i1} \times \boldsymbol{W}^{i1} & \cdots & t_D^{\alpha n1} \times \boldsymbol{W}^{n1} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1j} \times \boldsymbol{W}^{1j} & \cdots & t_D^{\alpha ij} \times \boldsymbol{W}^{ij} & \cdots & t_D^{\alpha nj} \times \boldsymbol{W}^{nj} \\ \vdots & & \vdots & & \vdots \\ t_D^{\alpha 1n} \times \boldsymbol{W}^{1n} & \cdots & t_D^{\alpha in} \times \boldsymbol{W}^{in} & \cdots & t_D^{\alpha nn} \times \boldsymbol{W}^{nn} \end{bmatrix}. \quad (8)$$

Step 5: Take a limit to the weighted supermatrix $\boldsymbol{W}^{\alpha}$. To obtain the DANP influential weights as global vector weights, raise the weighted supermatrix to a sufficiently large power k until the supermatrix has converged on a long-term stable supermatrix. In other words, we let $\lim_{g\to\infty}(\boldsymbol{W}^{\alpha})^{g}$, where g indicates a large amount of power.

3.3. Stage III

The VIKOR method procedure starts with the form of the $\boldsymbol{L}_k^p$ metric as shown in Equation (9).

$$L_k^p = \left\{ \sum_{j=1}^{n} [w_j(\left|f_j^* - f_{kj}\right|)/(\left|f_j^* - f_j^-\right|)]^p \right\}^{1/p}, \tag{9}$$

where w_j is the DANP influential weight of the jth criterion, f_j^* is the best level of aspiration, f_{kj} is the performance scores of the kth alternative and jth criterion, f_j^- is the worst level of tolerable, n is the number of criteria, and the range value of p is $1 \leq p \leq \infty$. There are two measures to formulate the ranking and gap used by VIKOR: $L_k^{p=1}$ (as S_k) and $L_k^{p=\infty}$ (as Q_k). Equation (10) shows the derivation of S_k, which is used for minimal average gap, and Equation (11) shows the derivation of Q_k, which is used for priority improvement.

$$S_k = L_k^{p=1} = \sum_{j=1}^{n} [w_j(\left|f_j^* - f_{kj}\right|)/(\left|f_j^* - f_j^-\right|)], \tag{10}$$

and

$$Q_k = L_k^{p=\infty} = \max_j \left\{ (\left|f_j^* - f_{kj}\right|)/(\left|f_j^* - f_j^-\right|) | j = 1, 2, \ldots, n \right\}. \tag{11}$$

It is shown in the compromise solution $\min_k L_k^p$ that the objective function is to minimize the synthesized gap, which will then improve its gap values for every criterion and dimension to get closest to the aspiration level. In addition, with regards to INRM, when the value of p is small (say p = 1), then the group utility is emphasized. Contrarily, if the value of p increases and goes to infinity, then every dimension or criterion's maximal gaps are given a greater priority for improvement. Therefore, $\min_k S_k$ emphasizes the maximum group utility; nevertheless, $\min_k Q_k$ emphasizes choosing the minimum value from the maximum number of individual gaps for prioritizing improvement.

There are four steps involved in VIKOR method:

Step 1: Find the level of aspiration and tolerability. We do a calculation to obtain the level of aspiration (indicated as the best f_j^* values) and the level of tolerability (indicated as the worst f_j^- values) for every criterion function, j = 1, 2, . . . , n. In the traditional way, it assumes that the jth function represents benefits: $f_j^* = \max_k f_{kj}$ and $f_j^- = \min_k f_{kj}$. In this study, we use performance scores with a scale range from 1 to 9 (where 1 indicates the worst to 9 indicates the best) in the performance questionnaire, in conjunction with the aspiration level. Thus, we plug the aspiration level with $f_j^* = 9$ and $f_j^- = 1$ as the best and worst value, respectively. Furthermore, a normalized weight rating matrix can transform the original rating matrix by using Equation (12):

$$r_{kj} = (\left|f_j^* - f_{kj}\right|)/(\left|f_j^* - f_j^-\right|). \tag{12}$$

Step 2: Compute the mean group utility and maximal gap. Calculate the values by $S_k = \sum_{j=1}^{n} w_j r_{kj}$, which refers to the synthesized gap for all criteria, and $Q_k = \max_j \left\{ r_{kj} | j = 1, 2, \ldots, n \right\}$, which refers to the maximal gap in criterion k for priority improvement.

Step 3: Compute the index value. We calculate the index value by using Equation (13).

$$R_k = v(S_k - S^*)/(S^- - S^*) + (1 - v)(Q_k - Q^*)/(Q^- - Q^*), \forall k = 1, 2, \ldots, m, \tag{13}$$

where S^* = $\min_i S_i$ (in case of S^* = 0 means all criteria have achieved the level of aspiration); S^- = $\max_i S_i$ (in case of S^- = 1 means the worst case); Q^* = $\min_i Q_i$ (can be set as Q^* = 0); Q^- = $\max_i Q_i$ (can be set as Q^- = 1); and v refers to the strategy weight of the maximum group utility. Contrarily, $1 - v$ refers to the average gap weight. In case of S^* = 0, S^- = 1,

$Q^* = 0$, and $Q^- = 1$, then Equation (13) can be rewritten in the simple form shown in Equation (14).

$$R_k = vS_k + (1 - v)Q_k. \quad (14)$$

Step 4: Compose a compromise solution by ranking or improving the alternatives. Sort the values of S_k, $Q_{k,}$ and R_k in decreasing order. Thus, we can propose a compromise solution for all alternatives by using the order of R_k. By using the VIKOR ranking method, we can determine the compromise solution, and it can be tailored to fit decision-makers' needs since it offers maximum group utility for the majority (shown by minimum S) and maximum regret for the opponents (shown by minimum Q).

4. Results and Discussions

In the process of promoting sustainability, Corporation U has tried to connect many partners together, sharing the same concepts to strengthen their operational profiles by coaching suppliers. Corporation U divides seven categories of suppliers into two tiers according to the procurement categories. The first tier includes process outsourcers, waste subcontractors, equipment and parts suppliers, manpower outsourcers, service outsourcers, and transportation categories. The second tier includes raw material suppliers. In this study, we focus on the equipment and parts suppliers that have three alternatives, namely, S_1, S_2, and S_3, who supply the equipment and parts to Corporation U. Utilizing the hybrid MCDM model, which incorporates DANP with VIKOR, we evaluated these suppliers and selected the best one. There are only five specific experts with broad experience in the SSS for equipment and parts at Corporation U. Four out of five experts are senior engineers with 5 to 10 years of working experience, and the last expert is the assistant manager with more than 10 years of working experience. They were asked to provide their feedback in a questionnaire form for the supplier evaluation purpose. There are six parts in the questionnaire to be filled in by the experts: (1) introduction; (2) description of dimension and criteria; (3) method for filling out; (4) criteria questionnaire; (5) performance questionnaire; and (6) basic personal data.

As part of the DEMATEL decision-making process, we assessed fifteen criteria across three dimensions and considered mutual relationship impacts as well. These fifteen criteria have been examined and analyzed through the rigorous literature review process. The selected criteria to pick the best sustainable supplier at Corporation U are shown in Table 1. The experts were asked through a criteria questionnaire to identify whether the relationships across dimensions and criteria had an influential effect. We evaluated the performance of each supplier based on the opinions of five experienced experts in a performance questionnaire with a scale of 1 (very poor performance) to 9 (the best performance). Then, we calculated the average performance scores of each supplier and applied the VIKOR method to achieve the performance and aspired level gaps of alternative suppliers. Table 2 shows the averaged initial direct-relationship matrix. This result was derived by comparing the influences and directions between criteria in pairwise comparisons. We use Equations (1) and (2) to calculate the normalized direct-influence matrix as shown in Table 3. The total influence matrix for criteria (Table 4) and dimensions (Table 5) were derived using Equation (3). The result in Table 5 was obtained from the total influence matrix for criteria as shown in Table 4, that classified five criteria within a dimension. The total direct-influence matrix, as shown in Table 6, results in vectors $\boldsymbol{r}$ and $\boldsymbol{s}$, which can be calculated using Equations (4) and (5). The highest positive difference $(r_i - s_i)$ means that dimension i or criterion i affects other dimension or criteria. For instance, Table 5 shows that the highest positive difference $(r_i - s_i)$ lies on the economic (D_1) dimension with the value of 0.122, indicating that this dimension affects other dimensions. The same analysis for Table 6, which shows the highest positive difference $(r_i - s_i)$ lies on the manufacturing capability (C_5) with the value of 1.041, indicates that this criterion affects other criteria in the scope of economic (D_1) dimension. Then, the INRM within dimensions and fifteen criteria of three dimensions were constructed as depicted in Figures 3 and 4, respectively.

Table 2. The initial influence matrix for criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	**Sum**
C_1	0.0	1.4	3.0	2.4	3.2	2.2	1.2	1.4	2.2	1.6	1.2	2.4	1.2	1.6	1.0	26.0
C_2	2.4	0.0	1.0	2.0	2.8	1.0	0.6	0.8	0.8	1.2	0.8	1.4	1.2	0.4	0.4	16.8
C_3	3.0	0.4	0.0	2.6	3.0	1.8	1.8	1.4	2.6	3.0	0.4	1.0	1.4	1.0	0.6	24.0
C_4	2.2	1.4	2.4	0.0	3.0	2.4	2.6	3.0	2.0	3.2	1.2	2.2	1.8	2.0	0.8	30.2
C_5	3.0	2.0	2.4	3.6	0.0	2.0	2.2	2.8	2.0	2.4	1.2	2.6	2.2	2.4	1.6	32.4
C_6	2.0	1.2	1.2	2.4	2.4	0.0	1.8	2.2	2.2	2.6	1.0	2.4	2.8	3.0	1.6	28.8
C_7	1.6	0.8	1.8	3.0	2.2	1.8	0.0	3.6	3.6	3.6	1.8	2.0	2.8	2.4	1.4	32.4
C_8	2.2	0.4	2.2	2.8	2.4	2.2	3.6	0.0	3.4	3.4	1.6	1.4	2.6	2.4	2.0	32.6
C_9	2.0	0.2	1.4	2.2	1.4	2.4	3.2	2.8	0.0	2.6	1.6	2.0	2.8	3.0	1.0	28.6
C_{10}	1.6	1.2	2.2	3.2	2.2	2.4	3.2	3.0	2.6	0.0	1.8	1.0	2.6	2.2	1.0	30.2
C_{11}	1.4	0.2	0.2	0.4	0.0	0.2	1.4	1.4	0.6	0.8	0.0	1.4	2.4	3.0	3.0	16.4
C_{12}	2.0	1.8	0.6	0.8	1.0	1.0	1.8	1.6	1.2	0.8	2.2	0.0	2.8	2.8	3.4	23.8
C_{13}	0.6	1.6	0.4	0.4	1.2	1.8	2.6	2.4	1.6	1.8	2.6	2.8	0.0	2.8	3.2	25.8
C_{14}	2.0	1.2	0.4	0.8	1.2	2.0	2.4	2.6	1.6	1.8	3.0	2.4	3.2	0.0	3.2	27.8
C_{15}	1.2	0.8	0.6	0.8	1.2	1.2	1.4	0.8	1.6	1.2	2.6	2.6	3.0	2.8	0.0	21.8
Sum	27.2	14.6	19.8	27.4	27.2	24.4	29.8	29.8	28.0	30.0	23.0	27.6	32.8	31.8	24.2	32.8

Table 3. The normalized direct-influence matrix for criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	0.000	0.043	0.091	0.073	0.098	0.067	0.037	0.043	0.067	0.049	0.037	0.073	0.037	0.049	0.030
C_2	0.073	0.000	0.030	0.061	0.085	0.030	0.018	0.024	0.024	0.037	0.024	0.043	0.037	0.012	0.012
C_3	0.091	0.012	0.000	0.079	0.091	0.055	0.055	0.043	0.079	0.091	0.012	0.030	0.043	0.030	0.018
C_4	0.067	0.043	0.073	0.000	0.091	0.073	0.079	0.091	0.061	0.098	0.037	0.067	0.055	0.061	0.024
C_5	0.091	0.061	0.073	0.110	0.000	0.061	0.067	0.085	0.061	0.073	0.037	0.079	0.067	0.073	0.049
C_6	0.061	0.037	0.037	0.073	0.073	0.000	0.055	0.067	0.067	0.079	0.030	0.073	0.085	0.091	0.049
C_7	0.049	0.024	0.055	0.091	0.067	0.055	0.000	0.110	0.110	0.110	0.055	0.061	0.085	0.073	0.043
C_8	0.067	0.012	0.067	0.085	0.073	0.067	0.110	0.000	0.104	0.104	0.049	0.043	0.079	0.073	0.061
C_9	0.061	0.006	0.043	0.067	0.043	0.073	0.098	0.085	0.000	0.079	0.049	0.061	0.085	0.091	0.030
C_{10}	0.049	0.037	0.067	0.098	0.067	0.073	0.098	0.091	0.079	0.000	0.055	0.030	0.079	0.067	0.030
C_{11}	0.043	0.006	0.006	0.012	0.000	0.006	0.043	0.043	0.018	0.024	0.000	0.043	0.073	0.091	0.091
C_{12}	0.061	0.055	0.018	0.024	0.030	0.030	0.055	0.049	0.037	0.024	0.067	0.000	0.085	0.085	0.104
C_{13}	0.018	0.049	0.012	0.012	0.037	0.055	0.079	0.073	0.049	0.055	0.079	0.085	0.000	0.085	0.098
C_{14}	0.061	0.037	0.012	0.024	0.037	0.061	0.073	0.079	0.049	0.055	0.091	0.073	0.098	0.000	0.098
C_{15}	0.037	0.024	0.018	0.024	0.037	0.037	0.043	0.024	0.049	0.037	0.079	0.079	0.091	0.085	0.000

Table 4. The total influence matrix for criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	r_i
C_1	0.253	0.184	0.277	0.327	0.342	0.299	0.324	0.330	0.331	0.332	0.258	0.330	0.344	0.348	0.264	4.544
C_2	0.235	0.097	0.159	0.229	0.248	0.186	0.208	0.214	0.200	0.222	0.170	0.214	0.237	0.211	0.167	2.998
C_3	0.328	0.152	0.192	0.329	0.332	0.285	0.335	0.325	0.338	0.364	0.228	0.284	0.340	0.323	0.242	4.396
C_4	0.358	0.209	0.296	0.306	0.381	0.348	0.416	0.427	0.377	0.428	0.299	0.370	0.417	0.413	0.301	5.346
C_5	0.393	0.234	0.305	0.417	0.311	0.350	0.419	0.435	0.389	0.420	0.313	0.396	0.444	0.440	0.337	5.604
C_6	0.333	0.195	0.246	0.350	0.344	0.263	0.374	0.385	0.360	0.388	0.283	0.360	0.425	0.422	0.312	5.041
C_7	0.358	0.201	0.292	0.407	0.375	0.351	0.369	0.467	0.440	0.461	0.337	0.385	0.471	0.451	0.339	5.704
C_8	0.377	0.192	0.305	0.405	0.385	0.364	0.470	0.371	0.439	0.459	0.334	0.373	0.469	0.455	0.356	5.756
C_9	0.333	0.166	0.253	0.348	0.319	0.334	0.417	0.406	0.303	0.394	0.302	0.351	0.429	0.427	0.299	5.080
C_{10}	0.340	0.201	0.288	0.393	0.358	0.348	0.433	0.428	0.393	0.340	0.317	0.338	0.439	0.420	0.307	5.342
C_{11}	0.188	0.094	0.117	0.160	0.149	0.150	0.218	0.216	0.181	0.194	0.147	0.205	0.264	0.275	0.240	2.796
C_{12}	0.269	0.175	0.177	0.237	0.241	0.231	0.299	0.292	0.264	0.265	0.265	0.230	0.351	0.345	0.309	3.950
C_{13}	0.253	0.181	0.187	0.250	0.266	0.273	0.348	0.342	0.300	0.318	0.296	0.330	0.302	0.373	0.325	4.346
C_{14}	0.308	0.181	0.202	0.279	0.285	0.295	0.364	0.367	0.319	0.338	0.323	0.339	0.413	0.317	0.342	4.671
C_{15}	0.232	0.139	0.164	0.220	0.228	0.221	0.272	0.255	0.257	0.258	0.262	0.287	0.338	0.328	0.201	3.662
s_i	4.558	2.603	3.459	4.659	4.563	4.297	5.265	5.259	4.892	5.181	4.134	4.794	5.683	5.548	4.341	

Table 5. The total influence matrix and influences given or received for dimensions.

Dimension	D_1	D_2	D_3	r_i	s_i	$r_i + s_i$	$r_i - s_i$
Economic (D_1)	0.276	0.332	0.308	0.916	0.794	1.709	0.122
Environmental (D_2)	0.311	0.390	0.376	1.077	0.996	2.073	0.081
Social (D_3)	0.207	0.273	0.296	0.777	0.980	1.757	−0.203

Table 6. The total direct-influence matrix on criteria.

Criteria	r_i	s_i	$r_i + s_i$	$r_i - s_i$
Quality of component (C_1)	4.544	4.558	9.103	−0.014
Delivery time (C_2)	2.998	2.603	5.601	0.396
Price of component (C_3)	4.396	3.459	7.856	0.937
Technical capability (C_4)	5.346	4.659	10.005	0.687
Manufacturing capability (C_5)	5.604	4.563	10.167	1.041
Environmental and energy management system (C_6)	5.041	4.297	9.339	0.744
Green manufacturing policy (C_7)	5.704	5.265	10.970	0.439
Practice of sustainable future (C_8)	5.756	5.259	11.015	0.496
Compliance of material used (C_9)	5.080	4.892	9.972	0.188
Recycling product and process (C_{10})	5.342	5.181	10.524	0.161
Supplier social responsibility (C_{11})	2.796	4.134	6.930	−1.338
Employee welfare and growth (C_{12})	3.950	4.794	8.743	−0.844
Organizational culture development (C_{13})	4.346	5.683	10.029	−1.337
Regulation compliance (C_{14})	4.671	5.548	10.220	−0.877
Occupational health and safety (C_{15})	3.662	4.341	8.003	−0.679

In order to solve the SSS problem, we combined the DEMATEL method with the ANP method. This combination was used to obtain the normalized matrix as shown in Table 7. Based on the construction of influence-unweighted supermatrix (see Table 8), we found dynamic relationships by evaluating the SSS criteria of Corporation U according to the DEMATEL process. The process of weighting the unweighted supermatrix is based on the total-influence normalized matrix. The result of a weighted supermatrix based on the extent of the impact of various criteria is shown in Table 9. By calculating the limiting power of the weighted supermatrix, it confirms that the supermatrix has been converged and becomes a long-term stable supermatrix (see Table 10), which reached a steady-state condition. Table 11 shows the global and local weights of all criteria and their ranks. In addition, the performance and gap of aspired level have also been presented in Table 11 as the result of the performance questionnaire and DANP local weight. We found that the priority in global weight of the first dimension is environmental (D_2), followed by social (D_3) and economic (D_1). This attractive result aligns with major concerns for industries around the world. As sustainability issues have grown, the economic factor has no longer to be the top priority of daily operations and supply chains; environmental and social factors come first instead. Furthermore, we extended the analysis of local weights to provide a priority of criteria in each dimension. The green manufacturing policy (C_7) is the first priority criteria in the environmental (D_2) dimension. Supplier's efforts to reduce pollution and undergo green transformation are important to achieve sustainability goals. By evaluating all these local and global weights, we are able to select the best alternatives using the VIKOR method.

Table 7. The new matrix obtained by normalizing matrix in criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	0.183	0.133	0.200	0.236	0.247	0.185	0.200	0.204	0.205	0.205	0.167	0.214	0.223	0.225	0.171
C_2	0.243	0.100	0.165	0.237	0.256	0.181	0.201	0.208	0.194	0.216	0.170	0.215	0.237	0.211	0.167
C_3	0.246	0.114	0.144	0.247	0.249	0.173	0.203	0.197	0.205	0.221	0.161	0.200	0.240	0.228	0.171
C_4	0.231	0.135	0.191	0.198	0.246	0.174	0.208	0.214	0.189	0.214	0.166	0.205	0.232	0.230	0.167
C_5	0.237	0.141	0.184	0.251	0.188	0.174	0.208	0.216	0.193	0.209	0.162	0.205	0.230	0.228	0.174
C_6	0.227	0.133	0.167	0.239	0.234	0.148	0.211	0.217	0.203	0.219	0.157	0.200	0.236	0.234	0.173
C_7	0.219	0.123	0.179	0.249	0.230	0.168	0.177	0.224	0.211	0.221	0.170	0.194	0.237	0.228	0.171
C_8	0.226	0.116	0.183	0.244	0.231	0.173	0.224	0.176	0.209	0.218	0.168	0.188	0.236	0.229	0.179
C_9	0.235	0.117	0.178	0.245	0.225	0.180	0.225	0.219	0.164	0.213	0.167	0.194	0.237	0.236	0.165
C_{10}	0.215	0.127	0.182	0.249	0.227	0.179	0.223	0.220	0.202	0.175	0.174	0.186	0.241	0.231	0.169
C_{11}	0.266	0.133	0.165	0.226	0.210	0.156	0.227	0.225	0.189	0.202	0.130	0.181	0.233	0.243	0.212
C_{12}	0.245	0.160	0.161	0.216	0.219	0.171	0.221	0.217	0.195	0.196	0.177	0.154	0.234	0.230	0.206
C_{13}	0.223	0.159	0.164	0.220	0.234	0.172	0.220	0.216	0.190	0.201	0.182	0.203	0.186	0.229	0.200
C_{14}	0.245	0.144	0.161	0.223	0.227	0.175	0.216	0.218	0.190	0.201	0.186	0.196	0.238	0.183	0.197
C_{15}	0.236	0.142	0.166	0.224	0.232	0.175	0.215	0.202	0.204	0.204	0.185	0.203	0.239	0.231	0.142

Table 8. The unweighted supermatrix.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	0.183	0.243	0.246	0.231	0.237	0.227	0.219	0.226	0.235	0.215	0.266	0.245	0.223	0.245	0.236
C_2	0.133	0.100	0.114	0.135	0.141	0.133	0.123	0.116	0.117	0.127	0.133	0.160	0.159	0.144	0.142
C_3	0.200	0.165	0.144	0.191	0.184	0.167	0.179	0.183	0.178	0.182	0.165	0.161	0.164	0.161	0.166
C_4	0.236	0.237	0.247	0.198	0.251	0.239	0.249	0.244	0.245	0.249	0.226	0.216	0.220	0.223	0.224
C_5	0.247	0.256	0.249	0.246	0.188	0.234	0.230	0.231	0.225	0.227	0.210	0.219	0.234	0.227	0.232
C_6	0.185	0.181	0.173	0.174	0.174	0.148	0.168	0.173	0.180	0.179	0.156	0.171	0.172	0.175	0.175
C_7	0.200	0.201	0.203	0.208	0.208	0.211	0.177	0.224	0.225	0.223	0.227	0.221	0.220	0.216	0.215
C_8	0.204	0.208	0.197	0.214	0.216	0.217	0.224	0.176	0.219	0.220	0.225	0.217	0.216	0.218	0.202
C_9	0.205	0.194	0.205	0.189	0.193	0.203	0.211	0.209	0.164	0.202	0.189	0.195	0.190	0.190	0.204
C_{10}	0.205	0.216	0.221	0.214	0.209	0.219	0.221	0.218	0.213	0.175	0.202	0.196	0.201	0.201	0.204
C_{11}	0.167	0.170	0.161	0.166	0.162	0.157	0.170	0.168	0.167	0.174	0.130	0.177	0.182	0.186	0.185
C_{12}	0.214	0.215	0.200	0.205	0.205	0.200	0.194	0.188	0.194	0.186	0.181	0.154	0.203	0.196	0.203
C_{13}	0.223	0.237	0.240	0.232	0.230	0.236	0.237	0.236	0.237	0.241	0.233	0.234	0.186	0.238	0.239
C_{14}	0.225	0.211	0.228	0.230	0.228	0.234	0.228	0.229	0.236	0.231	0.243	0.230	0.229	0.183	0.231
C_{15}	0.171	0.167	0.171	0.167	0.174	0.173	0.171	0.179	0.165	0.169	0.212	0.206	0.200	0.197	0.142

Table 9. The weighted supermatrix.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	0.055	0.073	0.074	0.070	0.071	0.065	0.063	0.065	0.068	0.062	0.071	0.065	0.059	0.065	0.063
C_2	0.040	0.030	0.034	0.041	0.042	0.038	0.036	0.033	0.034	0.037	0.035	0.043	0.042	0.038	0.038
C_3	0.060	0.050	0.043	0.057	0.055	0.048	0.051	0.053	0.051	0.053	0.044	0.043	0.044	0.043	0.044
C_4	0.071	0.071	0.074	0.060	0.076	0.069	0.072	0.070	0.071	0.072	0.060	0.058	0.059	0.059	0.060
C_5	0.075	0.077	0.075	0.074	0.057	0.068	0.066	0.067	0.065	0.065	0.056	0.058	0.062	0.061	0.062
C_6	0.511	0.498	0.477	0.481	0.479	0.409	0.464	0.478	0.497	0.494	0.444	0.485	0.490	0.499	0.498
C_7	0.553	0.555	0.560	0.575	0.574	0.584	0.488	0.617	0.620	0.615	0.646	0.629	0.626	0.613	0.612
C_8	0.562	0.573	0.544	0.590	0.596	0.600	0.617	0.486	0.604	0.608	0.640	0.615	0.614	0.619	0.574
C_9	0.565	0.536	0.565	0.521	0.533	0.561	0.582	0.576	0.451	0.558	0.537	0.555	0.539	0.539	0.578
C_{10}	0.566	0.595	0.610	0.591	0.575	0.605	0.609	0.602	0.587	0.483	0.574	0.557	0.572	0.571	0.579
C_{11}	0.497	0.506	0.480	0.495	0.482	0.450	0.486	0.481	0.478	0.498	0.341	0.464	0.477	0.488	0.486
C_{12}	0.636	0.639	0.596	0.611	0.611	0.572	0.556	0.538	0.556	0.531	0.475	0.403	0.532	0.514	0.532
C_{13}	0.664	0.705	0.713	0.689	0.685	0.675	0.680	0.676	0.680	0.690	0.611	0.614	0.487	0.624	0.626
C_{14}	0.671	0.629	0.678	0.683	0.679	0.671	0.652	0.655	0.676	0.661	0.638	0.602	0.602	0.479	0.607
C_{15}	0.509	0.496	0.509	0.498	0.519	0.496	0.490	0.513	0.474	0.483	0.557	0.540	0.524	0.517	0.372

Table 10. The stable matrix of ANP.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
C_1	13.280	13.280	13.280	13.280	13.280	13.011	13.011	13.011	13.011	13.011	12.623	12.623	12.623	12.623	12.623
C_2	7.695	7.695	7.695	7.695	7.695	7.539	7.539	7.539	7.539	7.539	7.314	7.314	7.314	7.314	7.314
C_3	9.819	9.819	9.819	9.819	9.819	9.621	9.621	9.621	9.621	9.621	9.334	9.334	9.334	9.334	9.334
C_4	13.375	13.375	13.375	13.375	13.375	13.104	13.104	13.104	13.104	13.104	12.713	12.713	12.713	12.713	12.713
C_5	13.014	13.014	13.014	13.014	13.014	12.751	12.751	12.751	12.751	12.751	12.370	12.370	12.370	12.370	12.370
C_6	98.019	98.019	98.020	98.019	98.020	96.037	96.037	96.037	96.037	96.037	93.170	93.170	93.170	93.170	93.170
C_7	123.510	123.510	123.510	123.510	123.510	121.012	121.012	121.012	121.012	121.012	117.399	117.399	117.400	117.400	117.400
C_8	122.284	122.284	122.284	122.284	122.283	119.810	119.810	119.810	119.810	119.810	116.233	116.233	116.234	116.234	116.234
C_9	112.327	112.327	112.327	112.327	112.327	110.055	110.055	110.055	110.055	110.055	106.771	106.770	106.770	106.770	106.770
C_{10}	117.790	117.789	117.789	117.790	117.790	115.407	115.407	115.407	115.407	115.407	111.963	111.963	111.963	111.963	111.963
C_{11}	96.185	96.185	96.185	96.185	96.185	94.240	94.240	94.240	94.239	94.239	91.427	91.427	91.427	91.426	91.426
C_{12}	107.998	107.998	107.998	107.998	107.998	105.813	105.813	105.813	105.813	105.813	102.656	102.655	102.655	102.655	102.655
C_{13}	130.771	130.771	130.771	130.771	130.771	128.126	128.126	128.126	128.126	128.126	124.302	124.302	124.302	124.302	124.302
C_{14}	128.069	128.069	128.069	128.069	128.069	125.478	125.479	125.479	125.478	125.479	121.733	121.734	121.734	121.734	121.734
C_{15}	102.109	102.109	102.108	102.109	102.109	100.043	100.043	100.043	100.043	100.043	97.056	97.056	97.057	97.057	97.057

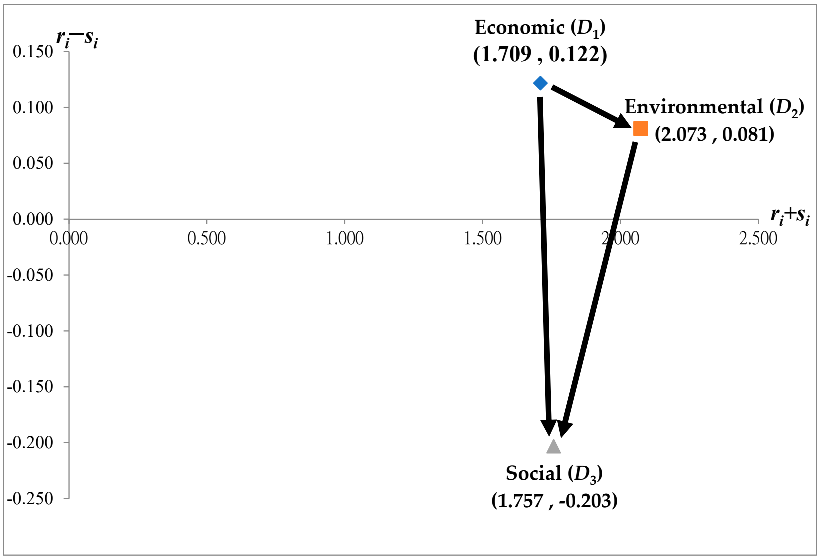
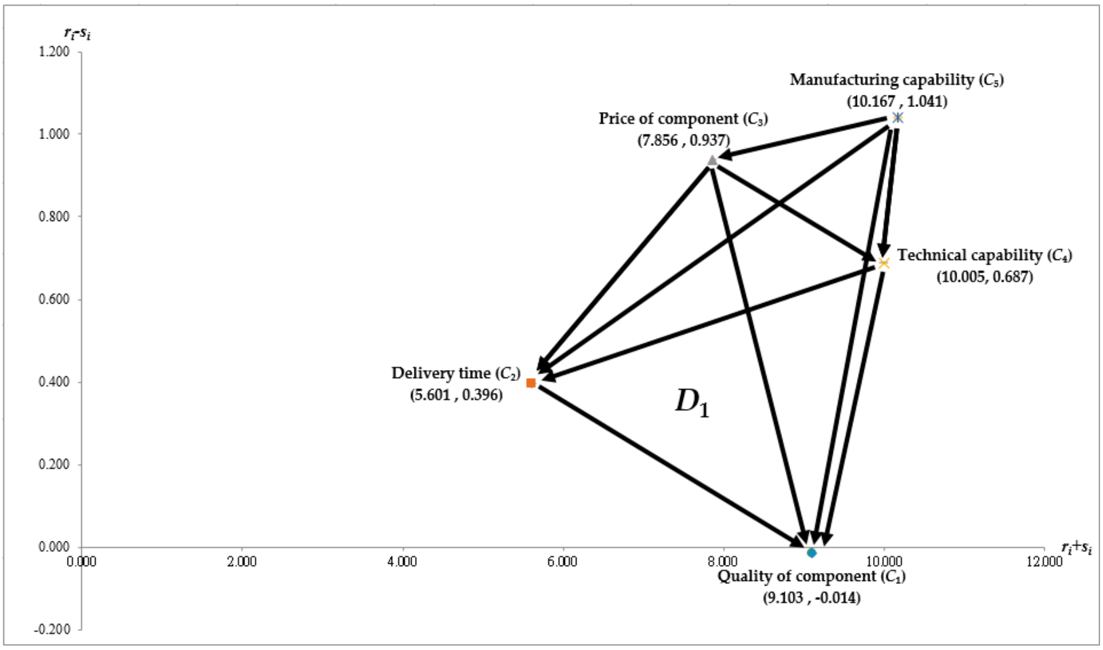
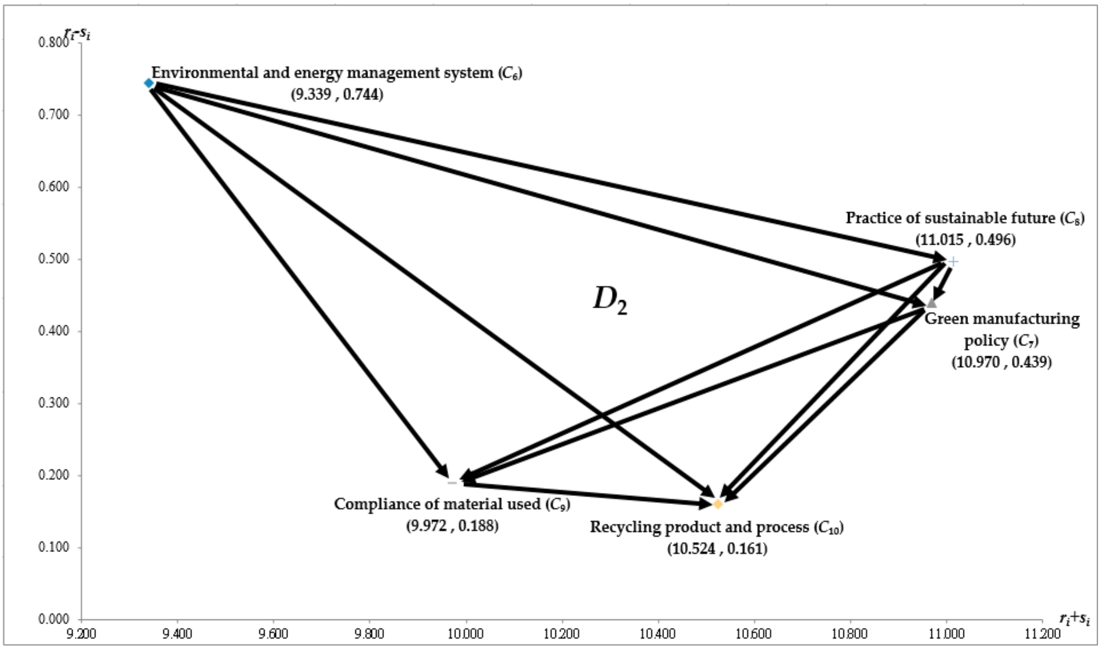


Figure 3. The INRM within dimensions.

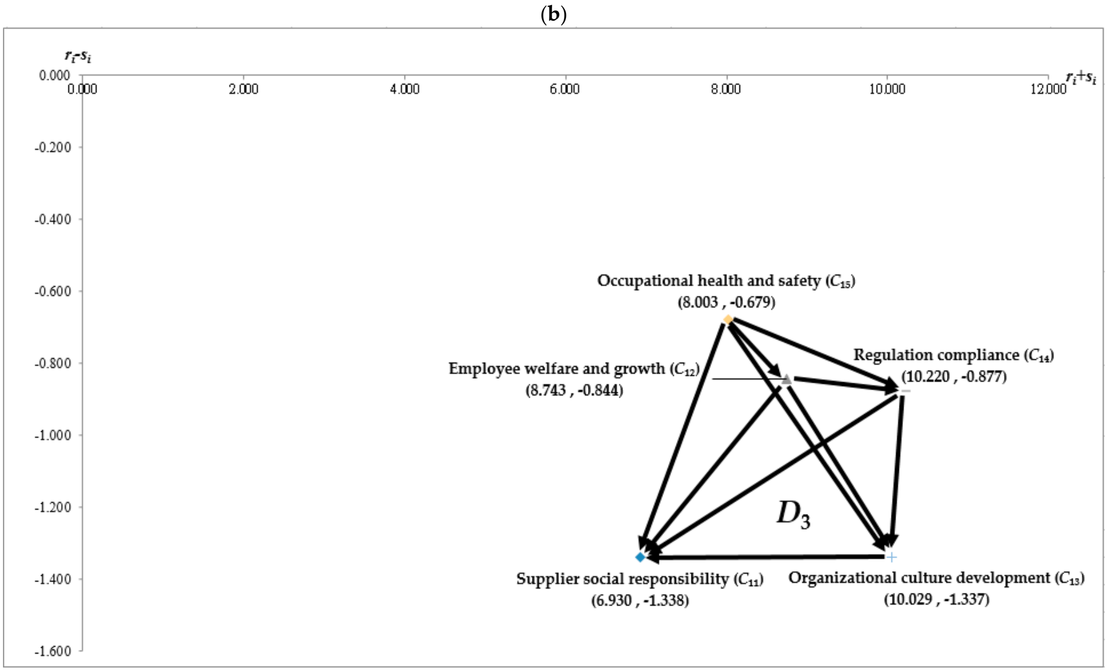


(a)

Figure 4. *Cont.*



(**b**)



(**c**)

Figure 4. The INRM of 15 criteria within (**a**) economic; (**b**) environmental; and (**c**) social dimension.

Table 11. The performance and aspired level gaps of alternative suppliers.

Dimensions and Criteria	Local Weight (Based on DANP)	Global Weight (Based on DANP)	Performance			Gap of Aspired Level		
			Supplier 1 (S_1)	Supplier 2 (S_2)	Supplier 3 (S_3)	Supplier 1 (S_1)	Supplier 2 (S_2)	Supplier 3 (S_3)
Economic (D_1)	**57.183 (3)**		**7.888**	**8.105**	**7.845**	**0.124**	**0.099**	**0.128**
Quality of component (C_1)	0.232(2)	13.280	8.800	8.200	8.800	0.022	0.089	0.022
Delivery time (C_2)	0.135(5)	7.695	8.600	8.800	8.800	0.044	0.022	0.022
Price of component (C_3)	0.172(4)	9.819	7.400	7.200	7.000	0.178	0.200	0.222
Technical capability (C_4)	0.234(1)	13.375	7.600	7.600	7.400	0.156	0.156	0.178
Manufacturing capability (C_5)	0.228(3)	13.014	7.200	8.800	7.400	0.200	0.022	0.178
Environmental (D_2)	**573.930 (1)**		**7.393**	**7.391**	**8.260**	**0.179**	**0.179**	**0.082**
Environmental and energy management system (C_6)	0.171(5)	98.019	8.600	8.400	8.800	0.044	0.067	0.022
Green manufacturing policy (C_7)	0.215(1)	123.510	5.800	6.400	8.200	0.356	0.289	0.089
Practice of sustainable future (C_8)	0.213(2)	122.284	8.600	7.200	8.200	0.044	0.200	0.089
Compliance of material used (C_9)	0.196(4)	112.327	7.400	7.800	8.400	0.178	0.133	0.067
Recycling product and process (C_{10})	0.205(3)	117.790	6.800	7.400	7.800	0.244	0.178	0.133
Social (D_3)	**565.131 (2)**		**8.200**	**7.393**	**8.164**	**0.089**	**0.179**	**0.093**
Supplier social responsibility (C_{11})	0.170(5)	96.185	8.200	5.800	8.200	0.089	0.356	0.089
Employee welfare and growth (C_{12})	0.191(3)	107.998	8.200	7.600	8.200	0.089	0.156	0.089
Organizational culture development (C_{13})	0.231(1)	130.771	8.200	7.600	8.200	0.089	0.156	0.089
Regulation compliance (C_{14})	0.227(2)	128.069	8.200	8.200	8.200	0.089	0.089	0.089
Occupational health and safety (C_{15})	0.181(4)	102.109	8.200	7.400	8.000	0.089	0.178	0.111
Total performance			**9328.279 (2)**	**8883.827 (3)**	**9802.628 (1)**			
Total gap						**159.768 (2)**	**209.152 (3)**	**107.063 (1)**

Note: The numbers in parenthesis represent the ranks of local weights in dimensions and criteria.

In this study, more relevant results are provided by using our proposed hybrid MCDM model. Performance of equipment and part suppliers can be assessed by analyzing the interdependence and feedback relationship between SSS dimensions and criteria. Additionally, the results can be used to determine where improvement gaps exist based on the aspired level criteria. The following are some of our findings:

1. Based on the INRM, as depicted in Figure 3 from the DEMATEL model, we can easily understand that three dimensions are influenced by each other: economic (D_1) influences environmental (D_2) and social (D_3); environmental (D_2) influences social (D_3). The influence of these relationships will assist managers in making better decisions. In order to enhance the environmental and social dimension, managers may suggest their suppliers focus on the economic dimension prior. Moreover, managers can use the INRM of D_1 as shown in Figure 4a to recommend their suppliers utilize smart manufacturing systems (C_5) to produce equipment and parts and improve operations, which leads to economic growth;
2. According to the results of DANP with VIKOR, as shown in Table 11, we found that the total performance of suppliers S_1, S_2, and S_3 were 9328, 8883, and 9802, respectively; that is, we can treat supplier S_3 as the best sustainable supplier to provide the electronic equipment and parts. Specifically, we found that supplier S_3 has an outstanding performance on the environmental (D_2) with 8.260 score. The difference score of supplier S_3 on that dimension is bigger compared to other two suppliers. In addition, suppliers S_1 and S_2 can perform benchmarking for supplier S_3 such that it would have better green operation and supply chain performance related with the environmental issues that Corporation U focuses on. Supplier S_3 has a great environmental responsibility to ensure a sustainable use of resources; that is, the use of renewable energy sources through intelligent energy management systems;
3. The only goal of traditional SSS approaches is selection of the best supplier. By using our hybrid MCDM model, we can rank and select the best sustainable supplier in addition to analyzing the gaps between their actual performance and the aspired performance level. For instance, currently, supplier S_3 is the best supplier of electronic equipment and parts. However, the gap of its aspired level is 107. In an attempt to minimize the gap of its aspired level, we propose an improvement suggestion for supplier S_3, namely, reducing the price of equipment and parts to address the largest gap of its aspired level (C_3); supplier S_3 should focus on improving their manufacturing capability (C_5) as it influences the production cost and reduces the gaps of aspired level. Supplier S_3 can apply smart manufacturing systems and use network technology to link their production with customers. Thus, it can cut down costs and any other production waste, which leads to the lower price of equipment and parts.

5. Conclusions

Sustainable supplier selection to promote sustainability in operations and supply chains has been a popular topic in recent years. The decision of SSS is a complicated process since it involves multiple dimensions and various interdependent criteria. In this study, we investigated the dimensions under triple bottom line framework and criteria that align for the electronics industry. In particular, sustainability issues have been raised to select the specific criteria, such as green manufacturing policy, the practice of sustainable future, and compliance of material used. A hybrid MCDM model using DANP and VIKOR was evaluated in an empirical case study. DANP can be used in the real world to overcome the problems of interdependency and feedback among dimensions and criteria. In combination with VIKOR's calculations based on DANP's global and local influential weights, managers can take decisions aimed at integrating performance and reducing gaps to aspiration levels. We do not only rank and select the best sustainable supplier, but also explain how to increase the suppliers' performance by reducing gaps across each dimension or criterion. By evaluating the largest gap to its aspired level, we can propose some improvements to minimize that gap. The presence of INRM also adds to the contribution of this study by showing the influence of relationships, which leads to valid decision-making. The INRM can help to analyze the relationship of criteria among each dimension; that is, which criteria influence other criteria that need to be improved. This study can thus contribute to enhancing and increasing resource utilization efficiency as well as achieving triple bottom line objectives for any industry.

A limitation of this study is the fact that the survey was conducted solely based on one category rather than being a comprehensive industrial survey. However, the hybrid MCDM model used on that category can also be applied to other categories and even for the second tier as the company continues to expand the risk assessment and management of tier 2 suppliers. After conducting a literature review, 15 criteria were identified in this study, though not all were included. An in-depth investigation could be carried out in the future to add more relevant criteria to similar studies. The object of the empirical case is only the electronics industry. By utilizing the proposed SSS framework, other relevant industries can also be examined. Future research may investigate using a dominance-based rough set approach or another new approach with the aim of reducing the gaps to the aspired level for optimal or suitable areas.

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